VOL. 80, NO. 5 JOURNAL OF GEOPHYSICAL RESEARCH FEBRUARY 10, 1975

Seismicity and Contemporary Tectonics of the Hebgen Lake–Yellowstone Park Region

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Detailed seismic monitoring of the Hebgen Lake–western Yellowstone Park region of Wyoming and Montana has delineated a zone of earthquakes extending 80 km in a direction N80°W from the northwest edge of the Yellowstone calderas to the Madison Valley. The active zone includes the epicentral area of the 1959 Hebgen Lake earthquake (magnitude 7.1). Focal depths ranged from near surface to 15 km in the Hebgen Lake region, whereas near the caldera boundaries the maximum focal depths decreased to 5 km. The abrupt change to shallow focal depths over and near the calderas may be related to increased temperature and pore pressure sufficient to inhibit brittle fracture. Six composite and four single-event fault plane solutions indicate north-south regional extension. Three composite fault plane solutions for earthquakes along the northwest boundary of the Yellowstone calderas indicate northwest-southeast crustal shortening, possibly from uplift on concentric fractures around the calderas.

The Hebgen Lake–Yellowstone Park region of the western United States (Figure 1) is located within the intermountain seismic belt at a pronounced change in trend of the regional seismic pattern from north to northwest. This location also corresponds to the intersection of the intermountain seismic belt with the central Idaho seismic belt, a secondary earthquake zone that extends westward through central Idaho into Oregon. Fault plane solutions for earthquakes along the intermountain seismic belt to the south indicate regional east-west extension, whereas north-south extension is outlined along the central Idaho seismic zone [*Smith and Sbar,* 1974]. The location of the Hebgen Lake–Yellowstone Park region at the intersection of these marked zones of crustal extension suggests that a complex stress distribution controls the contemporary tectonics.

To investigate the relationship of the seismicity and regional tectonics in the Hebgen Lake–Yellowstone region, a microearthquake survey was conducted during the summer of 1972. The objectives of the project were to outline earthquake distributions and to determine the contemporary stress patterns from fault plane solutions. The project included detailed monitoring in the western portion of Yellowstone Park and throughout the Hebgen Lake area (Figure 2). The project also included a study of the possible correlation of earthquake swarms with geothermal features in the geyser basins of Yellowstone Park.

TECTONICS

Most of the mountain ranges in the Hebgen Lake–Yellowstone region (Figure 2) were produced by north- to northwest-trending block faulting initiated in middle Tertiary time and similar to the tectonic development of the Basin and Range province to the southwest.

The Madison Range, north of the West Yellowstone basin, is a typical fault block that has been uplifted and truncated on the west by a steeply dipping normal fault. Using growth rings of the oldest trees along the scarp, *Pardee* [1950] estimated that the fault had major displacement late in the 1700's, the most recent movement being produced by the 1959 Hebgen Lake earthquake.

A 20-km northwest-trending zone of normal faults is exposed along the southern boundary of the Madison Range north of Hebgen Lake. The faults dip steeply south to southwest [*Witkind,* 1969], and recent movement has resulted in displacements up to 6.7 m accompanying the 1959 Hebgen Lake earthquake [*Myers and Hamilton,* 1969].

The Gallatin Range (Figure 2) forms a north-trending fault block in northwestern Yellowstone Park that is bounded on the east and west by north-trending normal fault zones. The east-trending Centennial Range, west of Hebgen Lake, tilts gently south and represents the upthrown block along the east-trending Centennial fault zone.

To the southeast the Snake River plain is covered by Pliocene and Quaternary basalt flows that extend along a northeast axis into Yellowstone Park. *Hamilton and Myers* [1966] have suggested that the Snake River plain is a lava-filled tension rift formed by crustal extension. *Christiansen and Blank* [1969] consider that the volcanic association of the Snake River plain evolved as a single volcanic-tectonic system that has grown progressively northeastward to the Yellowstone plateau. The northeastern extent of this tectonic system is now centered on two large resurgent calderas related to eruption of rhyolitic ashflow sheets [*Christiansen and Blank,* 1969]. Circular ring fractures mark the outer boundaries of the calderas (Figure 2).

Morgan [1972] pointed out that the Snake River plain may have been produced as a result of the relative westward motion of the North American plate overriding a mantle hot spot now beneath Yellowstone Park. *Smith and Sbar* [1974] have postulated that radial fractures resulting from the hot spot interaction with the North American plate may be represented by the Cenozoic faults of the intermountain seismic belt. The nature of the unusual tectonic-volcanic relationships of the Hebgen Lake–Yellowstone Park region is suggestive of a consistent pattern of foci of volcanism migrating northeastward along a tensional rift.

HISTORICAL SEISMICITY

It is convenient to divide the historical seismicity of the Hebgen Lake–Yellowstone region into two parts: the activity that occurred before 1959, primarily documented by felt reports, and the activity that has occurred since and is documented with modern seismographs. The first report of earthquakes in the Yellowstone Park area was given by F. V.

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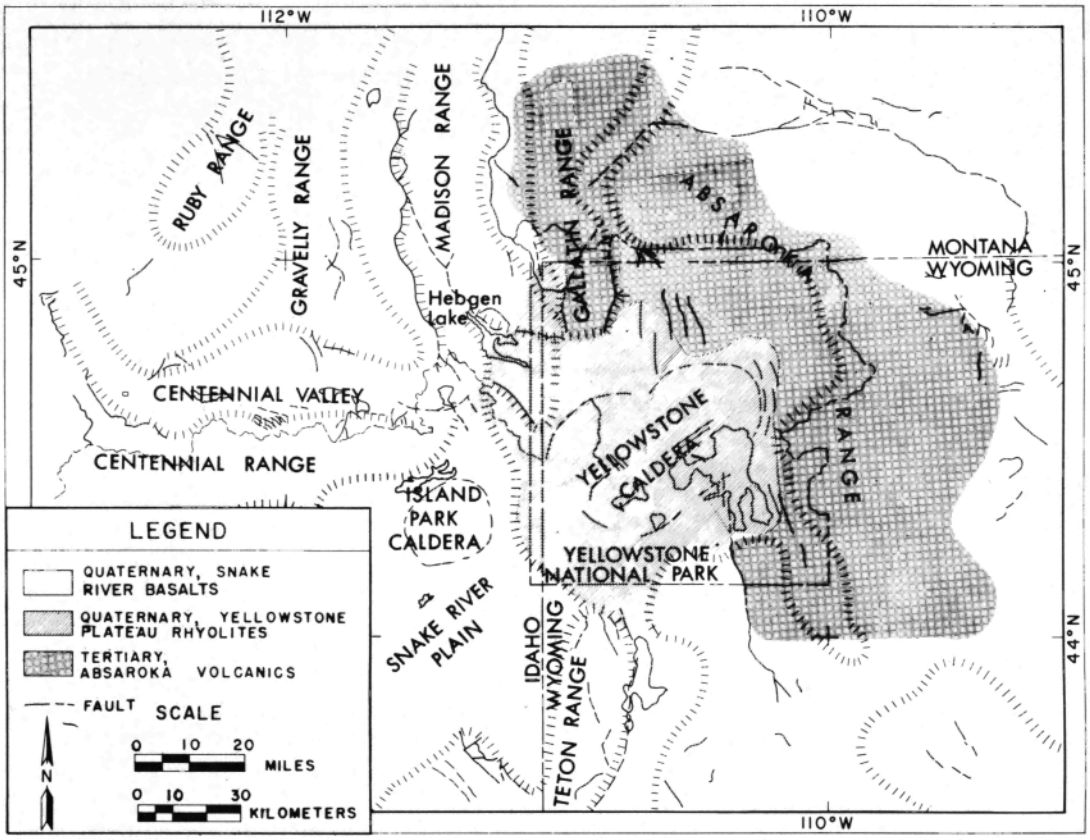


Fig. 1. Index map of the Hebgen Lake–Yellowstone Park region.

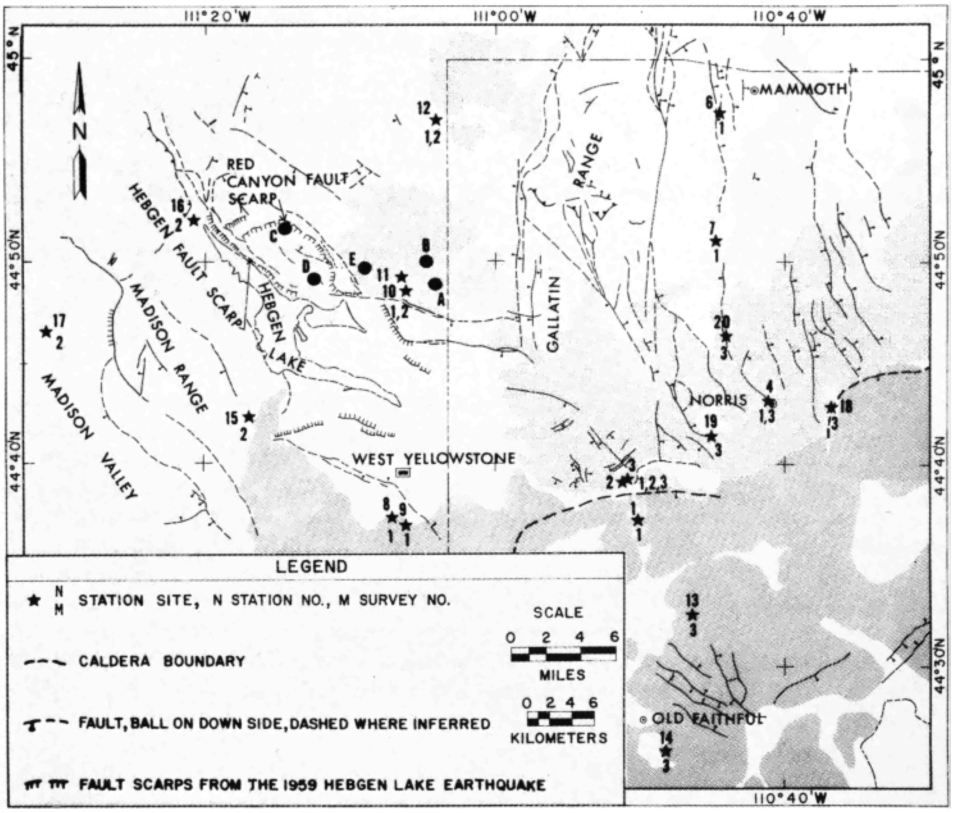


Fig. 2. Generalized tectonic map of the Hebgen Lake–western Yellowstone area with locations of seismograph stations occupied in the 1972 survey. Relocated epicenters of the 1959 Hebgen Lake earthquake are determined by the following methods: A, least squares [*Ryall*, 1962]; B, least squares (U.S. Coast and Geodetic Survey); C, compensating station pairs [*Ryall*, 1962]; D, systematic deviation [*Ryall*, 1962]; and E, least squares (this paper). The slanted line pattern represents Quaternary rhyolite; cross-hatched pattern, Quaternary welded tuff; and dotted pattern, Quaternary basalt.

Hayden, leader of the first scientific expedition in the area, who records that severe shocks were felt northeast of Yellowstone Lake in 1871 and that shocks continued to be felt for 1 month [*Fischer,* 1960]. From the late 1800's to 1959, at least 76 earthquakes were large enough to be felt in the Hebgen Lake–Yellowstone Park region.

A devastating earthquake of magnitude 7.1 occurred northeast of Hebgen Lake on August 17, 1959, costing 28 lives and over 11 million dollars in damage. Subsidence of as much as 6.7 m occurred in the West Yellowstone basin and as much as 2 m in the southern Madison Valley.

In a comprehensive examination of the Hebgen Lake earthquake, *Ryall* [1962] computed three different epicenters for this earthquake by different methods (Figure 2): epicenter A from Geiger's method of least squares (described by *Ryall* [1962]), epicenter D from the method of systematic deviation, and epicenter C by the method of compensating station pairs. Epicenter B was determined by the U.S. Coast and Geodetic Survey. We recomputed the epicenter for the Hebgen Lake earthquake by using *P* wave arrivals only from stations within 1000 km of the epicenter and a velocity model for western Montana derived by *McCamy and Meyer* [1964]. When an assigned focal depth of 5 km, based on our determinations of focal depths from microearthquakes, was used, the recomputed epicenter E was at 44°49.9′N, 111°08.8′W (origin time 06h 37m 15.2s). This location is 4 km east of the main Hebgen Lake fault scarp. Although our average rms residual was 0.5 s, indicative of a reasonably well determined solution, the calculated epicenter was still significantly displaced from the fault scarps. A possible explanation of this difference may be attributed to delayed arrivals received from stations in the southwest United States. Low P_n and low upper mantle velocities are characteristic of the region primarily including the Basin and Range province and could partly account for the northeast bias of teleseismically determined epicenters in the Hebgen Lake region.

Dewey et al. [1972] have recomputed the epicenter of 90 historical earthquakes in the Hebgen Lake–Yellowstone area, using the joint epicenter method with epicenter A as the fixed epicenter, with respect to which all other epicenters are located. The *Dewey et al.* [1972] epicenters of earthquakes with magnitudes of 4.0–7.1 are located along an east-trending zone 15 km north of the main Hebgen fault scarps and north of the zone of activity that we have located in our 1972 survey. We believe that their epicenter distribution represents a northeast bias produced by assuming epicenter A as the fixed location. Assuming that the bias is constant for the entire region and that the relative locations of epicenters are consistent, we adjusted the locations of the most accurately determined epicenters of *Dewey et al.* [1972], 5 km south and 10 km west (Figure 3). Thus the main zone of historical seismic activity is placed in coincidence with the activity outlined by our survey and in accordance with the location of the Cenozoic faults.

The distribution of the historical earthquakes (Figure 3) follows the easterly trend of the Hebgen fault zone and extends westward along the north side of the Centennial Range. To the east the epicenters trend southeast and terminate at the edge of the Yellowstone calderas. No historic events were located in the northeast part of the Snake River plain or in the Madison Range.

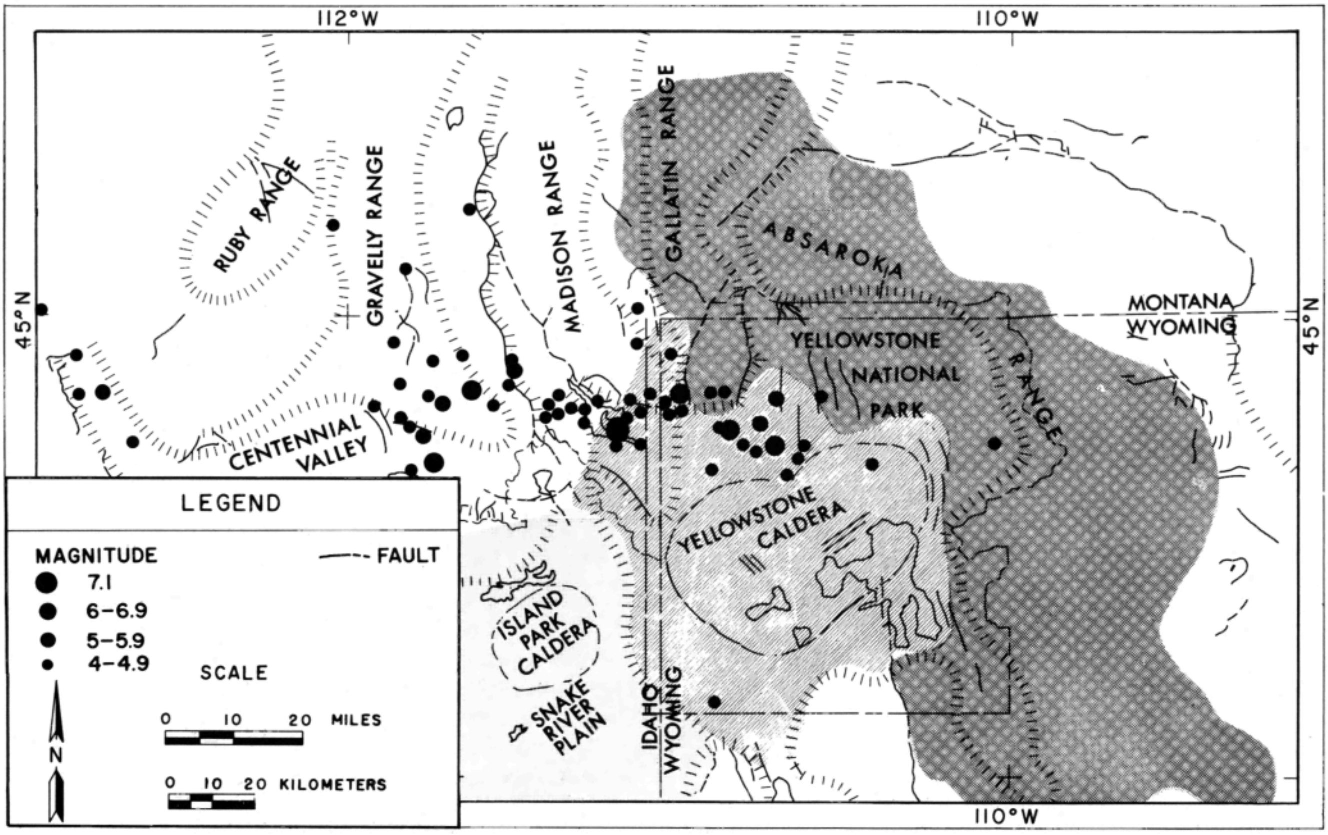


Fig. 3. Epicenters of historical earthquakes from 1925 to 1971. The epicenters of *Dewey et al.* [1972] have been shifted 5 km south and 10 km west to coincide with Cenozoic fault zones and contemporary seismic patterns. Magnitudes are approximately 4.0–7.1. The slanted line pattern represents Quaternary rhyolite; dotted pattern, Quaternary basalt; and diamond pattern, Tertiary basic volcanic rocks.

DATA COLLECTION

Six portable high-gain seismographs similar to those described by *Ward et al.* [1969] were used during the 1972 survey. Recording was on smoked paper records at 60 mm/min, a timing accuracy to 0.1 being allowed. Vertical component seismometers were used throughout the survey. Magnifications ranged from 10^5 at 10 Hz when seismometers were located on volcanic rocks to 3×10^6 at 10 Hz when seismometers were located on sedimentary rocks. An average of 16 events/d were recorded throughout the survey. Activity was as high as 43 events/d in the Norris geyser basin area and up to 32 events/d near the epicenter of the 1959 Hebgen Lake earthquake. An average of about 4 events/d were correlative on three or more instruments.

Earthquakes were located by Geiger's method for *P* wave arrivals. The program was a modification by *Winkler* [1971] of *Eaton*'s [1969] program that allowed the use of different near-surface velocity models for each station-epicenter pair. Thus differences in the station elevation and surface rock type were considered in the velocity model. Calculations of hypocenters were made for events identified on four or more stations. Events that were correlative on only three stations were assigned an arbitrary focal depth of 5 km, and only the epicenter coordinates and origin time were adjusted.

The generalized *P* wave velocity model was derived by *McCamy and Meyer* [1964] for a refraction profile 100 km northwest of the Hebgen Lake–Yellowstone area. It consisted of a near-surface layer varying in thickness from 1.8 to 2.5 km and a *P* wave velocity varying from 2.0 to 5.5 km/s, dependent on the bedrock type, a 20-km layer at 6.1 km/s, and a 25-km layer at 6.9 km/s underlain by an 8.4-km/s layer of semi-infinite thickness. All focal depths were relative to a datum 1.8 km above sea level.

A generalized inversion method outlined by *Michaels* [1973] was used to determine the resolution in epicenter and focal depth as a function of *P* arrival accuracy and the velocity model. With a fixed velocity model and an assumed timing accuracy to 0.1 s, epicenters were located within a circular area 0.5 km in radius for events within array 3 (Figure 2). For events just outside the array, epicenters were located within a 1.0-km-long elliptical area elongated in the direction of the event from the array. Events that were located at one array diameter outside the array were found to lie within an elliptically shaped area with a 3-km major axis and a 2-km minor axis. Hypocenters were found to lie within a vertically elongated ellipse with a major axis of 4 km and a minor axis of 2 km. On the basis of these results, we consider that the precision of our epicenter determinations was about ±1.0 km and that of the focal depths was ±2 km.

SEISMICITY

Figure 4 shows the epicenters of 182 earthquakes located from our 1972 survey and for which the rms travel time residuals were less than 0.1 s. Of these events, 76 have accurately determined hypocenters. Magnitudes were estimated to range from 1.0 to 2.5.

The epicenters delineate a pattern of earthquake activity that trends N80°W and is consistent with the trend determined for the historical seismicity. The active zone is more than 80 km in length and up to 20 km in width. The zone appears to terminate on the east at the edge of the Yellowstone calderas, and the western termination was not defined. On the basis of the historical seismicity, we would expect that the activity continues westward along the Idaho seismic zone.

From our data there appear to be three en echelon zones of diffuse earthquake activity, each of which trends northwesterly (Figure 4). The western zone is primarily associated with the northwest-trending Hebgen fault zone. The central zone of activity was located along the east side of the West Yellowstone basin at the east end of the Hebgen fault zone. The eastern and most active zone extends northwest from the Norris geyser basin and is probably associated with the northwest-trending faults on the south end of the Gallatin Range. A single east-west trend is not evident from our detailed data, but together the three zones of earthquakes outline a general east-west trend.

Cenozoic normal faults extending north from Norris geyser basin showed little earthquake activity during our survey, and no significant activity was determined during a 1-week observation period in the Upper or Lower geyser basins of Yellowstone Park, near Old Faithful. Further, we found little seismic activity north of the scarps of the 1959 Hebgen Lake earthquake, and no other activity was detected within the area outlined by Figure 4.

Hypocenter profile A-A′ has been constructed along a cross section of the main trend of seismic activity and extends from the Madison Valley on the west across the caldera boundary on the east (Figure 5). Focal depths range from near surface to a maximum of 15 km throughout the West Yellowstone basin. However, an abrupt change in maximum focal depth is clearly evident beginning about 10 km northwest of the caldera boundary, and only shallow events extend into the caldera. The absence of deep seismicity within and over the caldera may have resulted from factors such as high pore pressures or may be the result of (1) a recording period too short to detect less frequent deeper earthquakes or (2) perhaps an increased thermal gradient. *Brace and Byerlee* [1970], utilizing laboratory experiments of frictional sliding in rocks, suggest that brittle fracture is highly dependent on temperature for a stick slip earthquake model. They show that the increase of temperature above certain limits may inhibit stick slip failure and induce stable sliding. Hence if the stick slip model is applicable to in situ conditions, the decrease in focal depths within the Yellowstone caldera may reflect increased temperatures and increased pore pressure expected in this highly active geothermal environment.

Profile B-B′ (Figure 5) corresponds to a cross section perpendicular to the Hebgen fault. The well-defined southward dip of hypocenters is interpreted to indicate activity along the Hebgen fault with a range of focal depths from near surface to 15 km. The heavy line on profile B-B′ represents a 70° south-dipping plane and is the average of the fault planes determined from the fault plane solutions along the Hebgen fault zone described later.

EARTHQUAKE SWARMS

Within the intermountain seismic belt, particularly in Idaho and Montana, *Smith and Sbar* [1974] have shown that an unusually high percentage of the earthquake energy is released in swarms. Earthquake swarms located in our survey appear to be concentrated in the area between Hebgen Lake and the Norris geyser basin and constitute a major fraction of the seismicity of this zone. Isolated swarms have occurred throughout Yellowstone Park, and recently, in 1973, a major swarm was located on the southeast side of the Yellowstone caldera at the south end of Yellowstone Lake [*Smith et al.*, 1974].

On August 9, 1972, a pronounced change in the thermal ac-

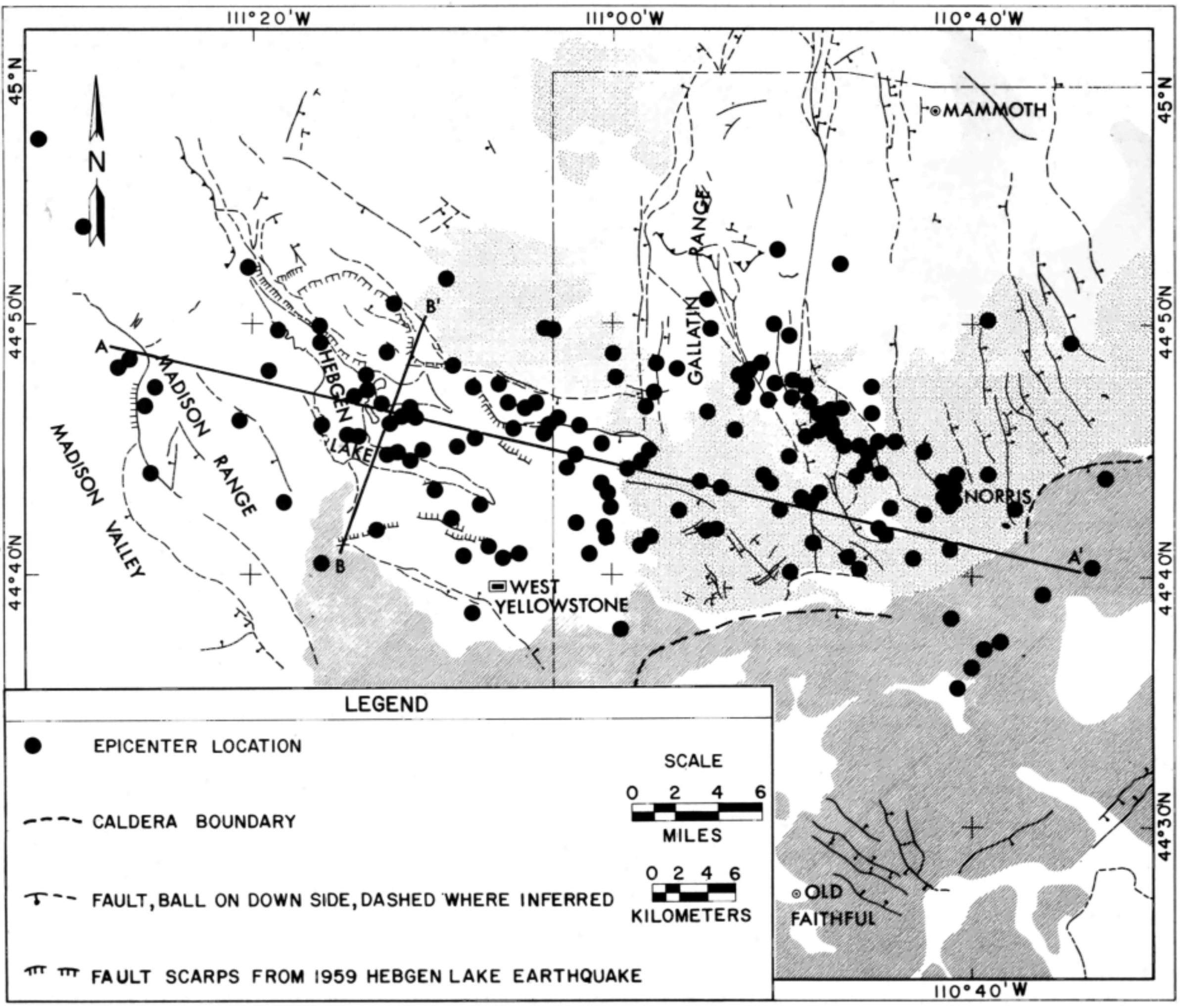


Fig. 4. Epicenter map of the Hebgen Lake–Yellowstone region for the 1972 survey. Data are plotted on a generalized tectonic map from the *U.S. Geological Survey* [1964, 1972].

tivity of the Norris geyser basin was noted with increased turbidity in thermal waters, development of new geothermal features, an increase in the temperature of many springs, and a change in the eruptive character of the major geysers (R. A. Hutchinson, unpublished report, 1972). The change in geothermal activity was followed shortly on August 11, 1972, by an earthquake swarm with several felt events. This sequence continued throughout early September 1972, up to 15 recorded events taking place per day.

To investigate the possible relationship between the earthquakes and the geothermal fluctuations at Norris geyser basin, we conducted a detailed microearthquake survey. Our station array (Figure 2) consisted of three stations located at the corners of an equilateral triangle centered about Norris geyser basin, a fourth station being located at the center of the array. For the first week of recording, begun August 24, 1972, microearthquakes up to about magnitude 1 occurred at a rate of 5 events/d. However, on September 1, 1972, the local seismic activity at Norris geyser basin increased rather suddenly to over 15 events/d. The activity was notable in that the earthquakes occurred in three groups of multiple events, each group consisting of up to eight earthquakes. Individual events were similar in character but were separated by nearly constant times of 10–20 s (Figure 6). Most of the events were located in a north-trending zone 1 km east of Norris geyser basin with focal depths from 1 to 3 km. The multiple-event occurrence and its close spatial association with the geyser basin suggest a source relationship, perhaps one in which hot fluids migrating through a permeable medium could systematically increase pore pressures and induce the earthquakes.

That earthquake swarms and geothermal activity are directly related in the Norris geyser basin has not been sufficiently documented by our data. However, the spatial relationship of the shallow-focus microearthquakes occurring in a swarm sequence and the periodic nature of events occurring very near the geyser basin and probably within the zone of convective hot water flow indicate a possible relationship. Further, R. A. Hutchinson (unpublished report, 1972) has documented seven major periods of geothermal fluctuations at Norris geyser basin since 1947, four of which coincided

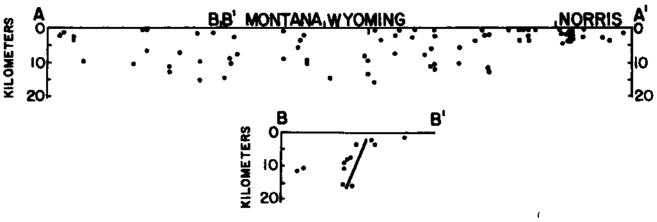


Fig. 5. Hypocenter profiles A-A', parallel to the N80°W trend of seismic activity, and B-B', perpendicular to the Hebgen fault zone. The solid line represents a dip of 70°S.

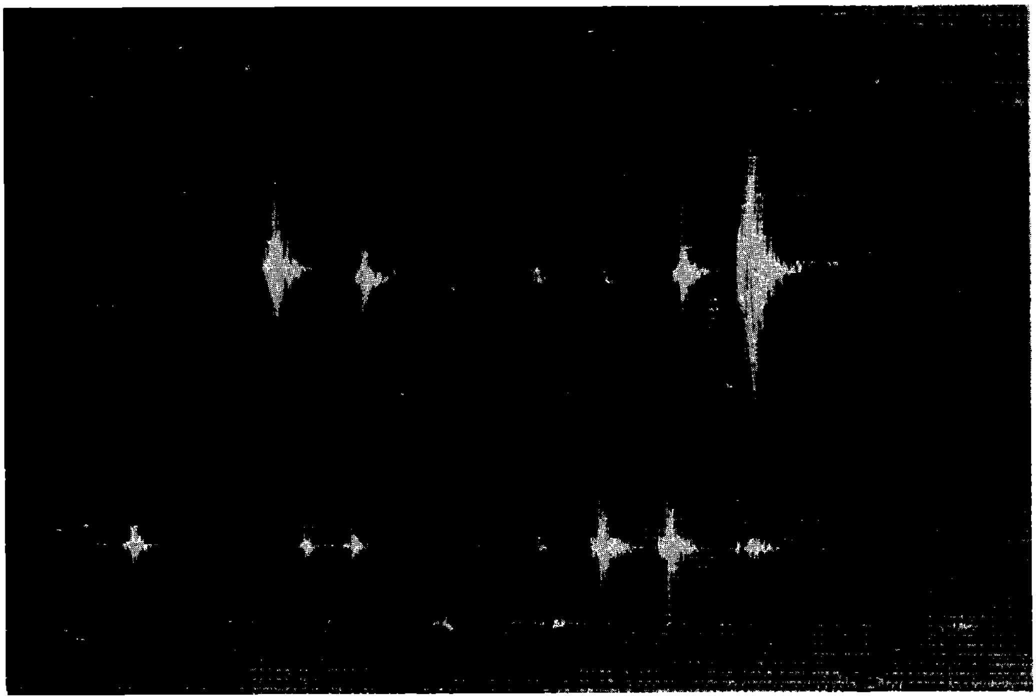


Fig. 6. Seismogram showing multiple events recorded at Norris geyser basin. Fine ticks are 1-s timing marks.

within a few days with marked increases in the local seismic activity.

Mogi [1963] suggests that the mechanism of earthquake swarms may be related to a concentrated stress distribution in heterogeneous source material. Such conditions are likely in volcanic and geyser areas where stress concentrations may have been produced by high fluid pressures and high temperatures. These in turn can reduce the effective rock strength and induce swarm activity. *Rinehart* [1972] has suggested that deformational strain produced by earth tidal forces in geyser basins could be expected to influence heat flow variation resulting in crack and fissure dilatation allowing convective fluid to permeate the surrounding material. This mechanism could account for the formation of gas and increased water temperature in the geysers that would in turn decrease the effective stress enough to allow fracture and produce small earthquakes.

Detailed monitoring within the Upper and Lower geyser basins, including the Old Faithful area, however, showed no microearthquake activity during our survey. A distinguishing characteristic of the Upper and Lower geyser basins is their location within the Yellowstone calderas rather than outside, like the Norris geyser basin. R. O. Fournier (personal communication, 1974) indicates that the Norris geyser basin has the hottest fluid reservoir in Yellowstone Park, which may account for the increased geothermal and associated seismic activity.

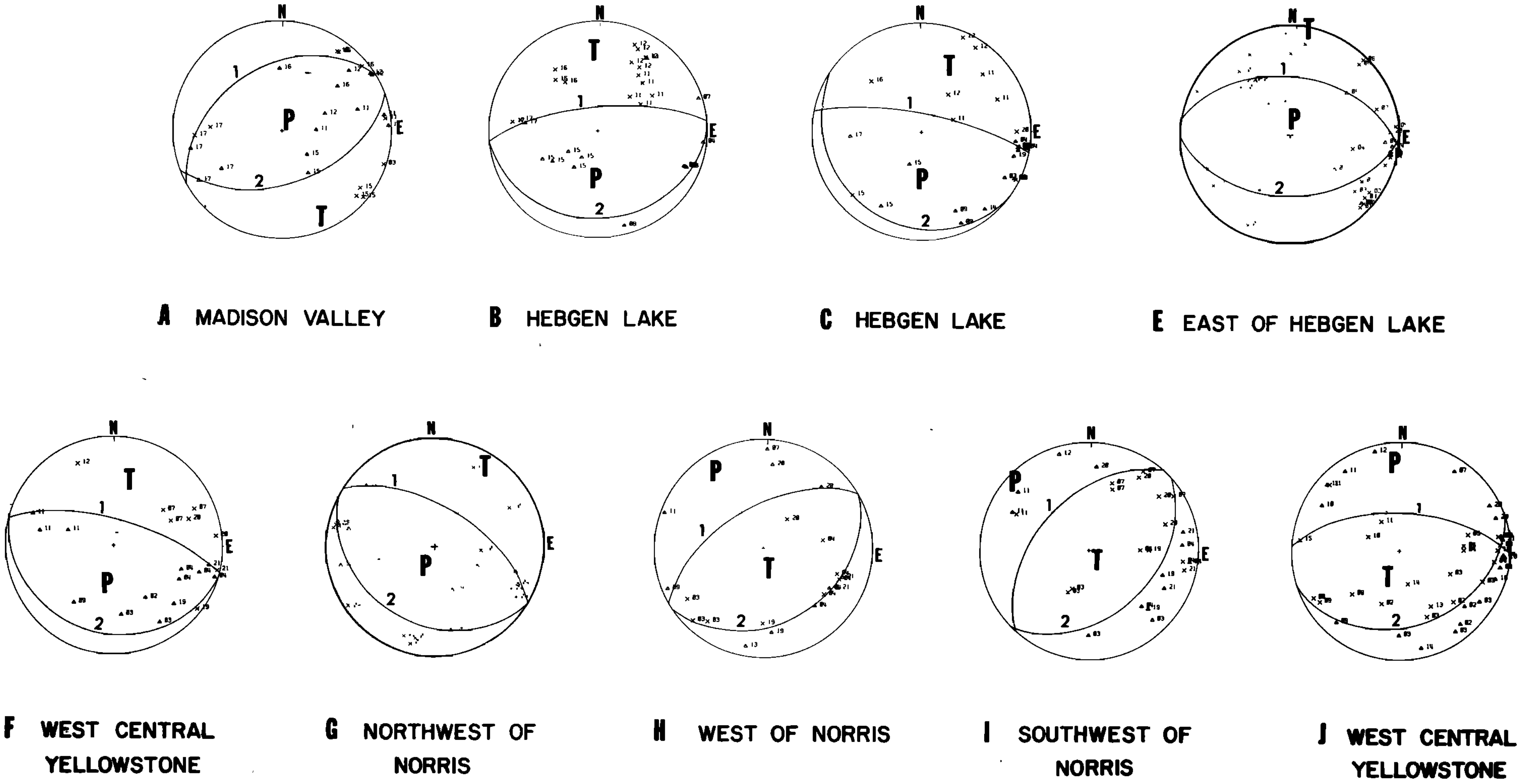
CONTEMPORARY TECTONICS

The seismograph station distribution for the Hebgen Lake–Yellowstone Park survey was designed to provide areal coverage for fault plane solutions. These data were sought to obtain an estimate of the regional stress pattern around the intersection of the regional north-trending intermountain seismic belt with the Yellowstone calderas. Nearly all the seismograph stations received direct arrivals, and upper-hemisphere equal area projections were used to display the *P* wave first-motion data. Figure 7 shows nine composite fault plane solutions, A, B, C, and E–J, obtained during the 1972 survey (Table 1). Figure 8 shows all fault plane solutions for the Hebgen Lake–Yellowstone region, solutions D and M being taken from *Smith and Sbar* [1974] and solutions L, N, and K being determined by *Dewey et al.* [1972].

Fault plane solution D of the 1959 Hebgen Lake earthquake indicates a N80°W nodal plane on a normal fault downthrown to the south and consistent with the surface displacement of the Hebgen fault. Solutions N, A, B, C, E, F, and G are for earthquakes that occurred along a regional east-west zone of weakness coincident with the N80°W zone of seismicity and are all indicative of normal fault motion with the downthrown blocks to the south. Note the similarity of these solutions to solution D of the 1959 Hebgen Lake earthquake, suggestive that the activity is closely related, perhaps some of it as aftershocks.

Solution A is similar to the solutions to the east along the Hebgen Lake fault zone but is inconsistent with the northwest-trending faults along the west side of the Madison Range. We interpret this similarity to imply that the contemporary stress pattern in this particular area is controlled primarily by north-south extension, whereas the northwest-trending faults were produced during an earlier period of extension similar to that of the intermountain seismic belt. Solution M on the west side of the Madison Valley is inconsistent with movements on the east-trending normal faults but indicates regional north-south extension consistent with that found along the Hebgen fault. Solution L is the only solution for which the *T* axis strikes east, consistent with north-trending faulting along the Madison Range, and probably represents the northward continuation of the stress field associated with the intermountain seismic belt.

The eastern end of the active seismic zone in Yellowstone Park is characterized by north-south regional extension, including the microearthquakes in the Gallatin Range from solutions G and F and the larger historic event, solution K.



A MADISON VALLEY

B HEBGEN LAKE

C HEBGEN LAKE

E EAST OF HEBGEN LAKE

F WEST CENTRAL YELLOWSTONE

G NORTHWEST OF NORRIS

H WEST OF NORRIS

I SOUTHWEST OF NORRIS

J WEST CENTRAL YELLOWSTONE

Fig. 7. Composite fault plane solutions for the 1972 survey. Upper-hemisphere equal area projections. Crosses indicate compressions; triangles, dilatations; P, pressure axes; T, tension axes; and solid circles, *P* axes. Numbered symbols denote stations that recorded first motions.

TABLE 1. Composite Fault Plane Solution Data

	Nodal Plane 1		Nodal Plane 2		*P* Axis		*T* Axis	
Solution*	Strike	Dip	Strike	Dip	Trend	Plunge	Trend	Plunge
A	N60°E	40°SW	N68°E	50°NW	N24°E	82°S	N26°W	8°N
B	N84°E	72°S	N84°E	18°N	N 4°W	64°N	N 6°W	26°S
C	N78°W	76°S	N57°W	14°N	N 2°W	62°N	N16°E	28°S
E	N87°W	46°S	N89°W	44°N	N90°E	88°E	N3°E	2°W
F	N76°W	70°S	N74°W	20°N	N16°E	65°N	N16°E	25°S
G	N58°W	60°SW	N58°W	30°NE	N60°E	75°NE	N60°E	15°SW
H	N58°E	58°SE	N58°E	32°NW	N32°W	12°SE	N32°W	78°NW
I	N41°E	50°SE	N46°E	40°NW	N42°W	6°SE	N42°W	84°NW
J	N90°E	60°S	N72°E	30°N	N 6°W	16°S	N28°E	74°N

* See Figure 7 For further data.

However a hint of the *T* axes' beginning to trend north-northeasterly can be seen in solutions G and F.

Fault plane solutions H, I, and J along the northwest side of the Yellowstone calderas and near the southern portion of the West Yellowstone basin show a distinctively different pattern indicative of thrust faulting. The *P* axes are generally horizontal and trend radial to the caldera boundaries. It is difficult to explain this abrupt change in a regional stress pattern dominated by north-south extension to a pattern of crustal shortening. One interpretation suggests a localized effect produced by resurgence or uplift of the inner caldera material with crustal shortening perpendicular to the caldera boundary. Downfaulted blocks within the Yellowstone calderas may be rising in response to magma chamber inflation, the upper crustal layers acting in a passive role and transmitting crustal stress only a short distance. Focal depths for the earthquakes used to obtain solutions H, I, and J did not exceed 5 km, indicative of shallow faulting.

Another interpretation of this diverse stress pattern may be a generalized rotation of the West Yellowstone basin from a

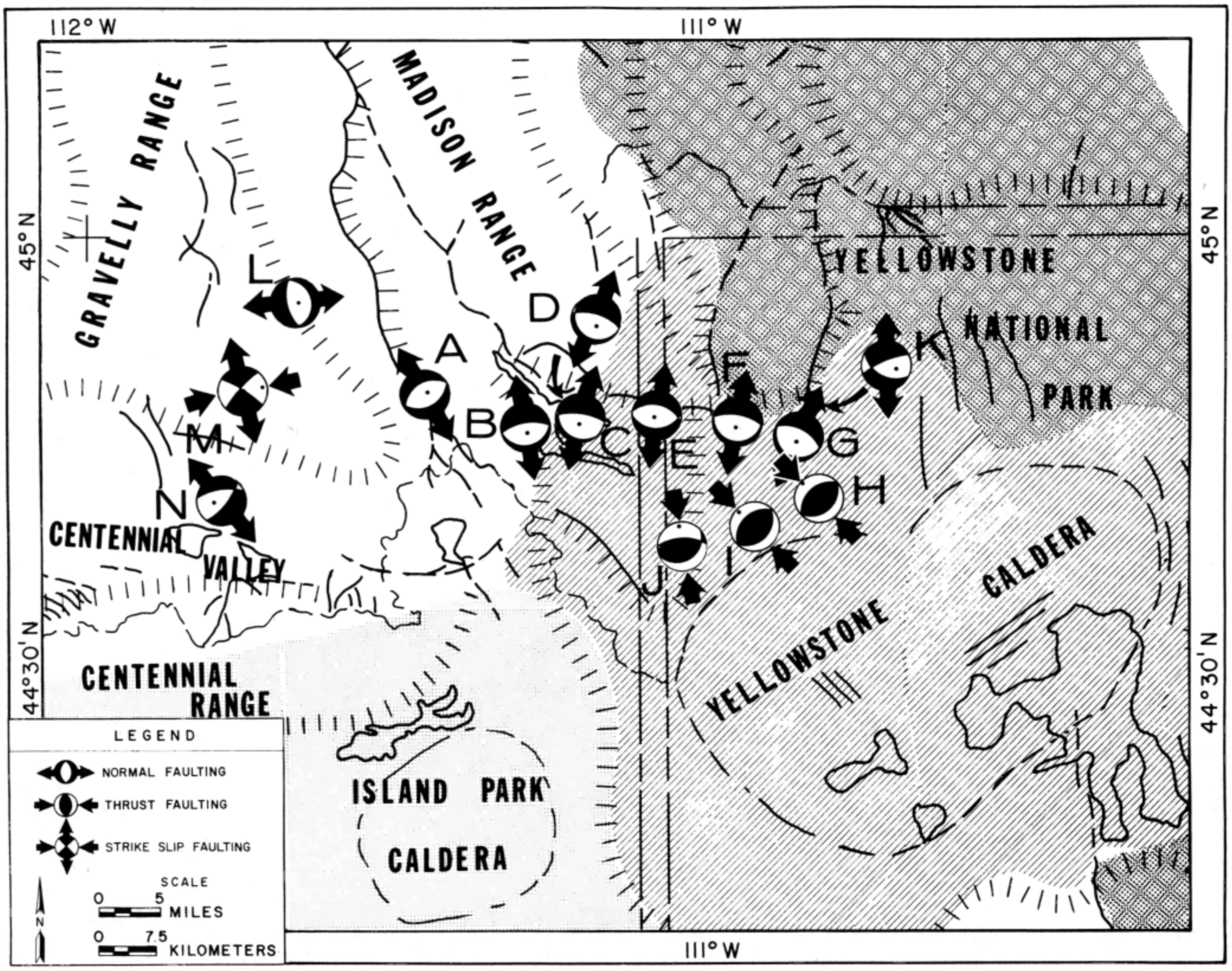


Fig. 8. Fault plane solutions for the Hebgen Lake-Yellowstone area. Upper-hemisphere equal area projections. Outward-directed arrows represent horizontal projections of *T* axes, and inward-directed arrows represent horizontal projections of *P* axes.

downward motion along the northern side of the Hebgen fault zone, the result being upward rotation along shallow thrust faults at the southern margin of the basin.

Our data are not sufficient or detailed enough to argue or reaffirm either of these possible interpretations. Regional releveling and geodetic measurements across the Hebgen fault zone and across the Yellowstone caldera would provide useful data to explore both mechanisms.

Acknowledgments. We wish to express our appreciation to William Dumire, chief Park naturalist, and Stanley Cantor, assistant chief Park naturalist, Yellowstone National Park, for their cooperation and assistance. Partial funding was provided by the Department of Commerce, NOAA, grant 04-3-022-13. Special thanks are expressed to the Lamont-Doherty Geological Observatory of Columbia University for allowing the use of a portable seismograph. Robert Otis, Richard Heaney, and Terry Daw assisted in the field work. W. T. Parry, J. W. Dewey, and M. L. Sbar reviewed the manuscript.

REFERENCES

Brace, W. F., and J. D. Byerlee, California earthquakes: Why only shallow focus?, *Science, 168,* 1573–1576, 1970.

Christiansen, R. L., and H. R. Blank, Jr., Volcanic evolution of the Yellowstone rhyolite plateau and eastern Snake River plain (abstract), in *Symposium on Volcanoes and Their Roots,* pp. 220–221, International Association of Volcanology and Chemistry of the Earth's Interior, Oxford, 1969.

Dewey, J. W., W. H. Dillinger, J. Taggert, and S. T. Algermissen, A technique for seismic zoning: Analysis of earthquake locations and mechanisms in northern Utah, Wyoming, Idaho and Montana, in *Proceedings of the Internal Conference on Microzonation for Safer Construction in Research and Applications,* vol. 2, pp. 879–894, University of Washington, Seattle, 1972.

Eaton, J. P., Hypolayer, a computer program for determining hypocenters of local earthquakes in an earth consisting of uniform flat layers over a half space, open file report, U.S. Geol. Surv., Menlo Park, Calif., 1969.

Fischer, A. J., *Yellowstone's Living Geology,* Western Lithoprint, Billings, Mont., 1960.

Hamilton, W., and W. B. Myers, Cenozoic tectonics of the western United States, *Rev. Geophys. Space Phys., 4,* 509–549, 1966.

McCamy, K., and R. P. Meyer, A correlation method of apparent velocity measurement, *J. Geophys. Res., 69,* 691–699, 1964.

Michaels, P. J., An application of the generalized linear inverse method in the location of microearthquakes and simultaneous velocity model determination, M.S. thesis, Univ. of Utah, Salt Lake City, 1973.

Mogi, K., Some discussions on aftershocks, foreshocks and earthquake swarms, *Bull. Earthquake Res. Inst. Univ. Tokyo, 41,* 615–658, 1963.

Morgan, W. J., Deep mantle convection plumes and plate motions, *Amer. Ass. Petrol. Geol. Bull., 56,* 203–213, 1972.

Myers, W. F., and W. Hamilton, Deformation accompanying the Hebgen Lake earthquake of August 17, 1959, The Hebgen Lake, Montana, Earthquake of August 17, 1959, *U.S. Geol. Surv. Prof. Pap., 435,* 37–98, 1969.

Pardee, J. T., Late Cenozoic block faulting in western Montana, *Bull. Seismol. Soc. Amer., 52,* 235–271, 1950.

Rinehart, J. S., Fluctuations in geyser activity caused by variations in earth tidal forces, barometric pressure, and tectonic stresses, *J. Geophys. Res., 77,* 342–350, 1972.

Ryall, A., The Hebgen Lake, Montana, earthquake of August 17, 1959, *P*-waves, *Bull. Seismol. Soc. Amer., 52,* 235–271, 1962.

Smith, R. B., and M. L. Sbar, Contemporary tectonics and seismicity of the western United States with emphasis on the intermountain seismic belt, *Geol. Soc. Amer. Bull., 85,* 1205–1218, 1974.

Smith, R. B., R. T. Shuey, R. F. Freidline, R. Otis, and L. Alley, Seismic and magnetic evidence for the Yellowstone caldera: An apex of intraplate deformation? (abstract), *Geol. Soc. Amer. Abstr. Program, 6,* 256, 1974.

U.S. Geological Survey, The Hebgen Lake, Montana, earthquake of August 17, 1959, *U.S. Geol. Surv. Prof. Pap. 435,* plate 5, 1964.

U.S. Geological Survey, Geological map of Yellowstone National Park, Map I-711, Reston, Va., 1972.

Ward, P. L., G. Pálmason, and C. Drake, Microearthquake survey and the mid-Atlantic ridge in Iceland, *J. Geophys. Res., 74,* 665–684, 1969.

Winkler, P. L., Source mechanisms of earthquakes associated with coal mines in eastern Utah, M.S. thesis, Univ. of Utah, Salt Lake City, 1971.

Witkind, I. J., Reactivated faults north of Hebgen Lake, The Hebgen Lake, Montana, earthquake of August 17, 1959, *U.S. Geol. Surv. Prof. Pap. 435,* 37–50, 1969.

(Received May 21, 1974;
revised August 16, 1974;
accepted October 10, 1974.)